

Quantum mechanical model for J/ψ suppression in the LHC era

C. Peña^a, D. Blaschke^{a,b}

^a*Institute for Theoretical Physics, University of Wrocław, pl. M. Borna 9, 50-204 Wrocław, Poland*

^b*Bogoliubov Laboratory for Theoretical Physics, JINR Dubna, Joliot-Curie str. 6, 161980 Dubna, Russia*

Abstract

We discuss the interplay of screening, absorption and regeneration effects, on the quantum mechanical evolution of quarkonia states, within a time-dependent harmonic oscillator (THO) model with complex oscillator strength. We compare the results with data for $R_{AA}/R_{AA}(\text{CNM})$ from CERN and RHIC experiments. In the absence of a measurement of cold nuclear matter (CNM) effects at LHC we estimate their role and interpret the recent data from the ALICE experiment. We also discuss the temperature dependence of the real and imaginary parts of the oscillator frequency which stand for screening and absorption/regeneration, respectively. We point out that a structure in the J/ψ suppression pattern for In-In collisions at SPS is possibly related to the recently found $X(3872)$ state in the charmonium spectrum. Theoretical support for this hypothesis comes from the cluster expansion of the plasma Hamiltonian for heavy quarkonia in a strongly correlated medium.

Keywords: Heavy quarkonia, Quark-gluon plasma, Mott effect

1. Introduction

The J/ψ suppression at CERN and RHIC has been quantified by measurements of the nuclear modification factor R_{AA} [1]. This set of experimental data is commonly normalized to the baseline of cold nuclear matter (CNM) effects $R_{AA}(\text{CNM})$. The results are scaled with the multiplicity of charged particles $\frac{dN_{ch}}{d\eta}|_{\eta=0}$ [2, 3, 4, 5].

A key problem to be solved in heavy-ion collisions is that the usage of heavy quarkonia states as a probe for the diagnostics of the quark-gluon plasma (QGP) requires the knowledge of the baseline for their production and evolution characteristics in situations when a QGP is absent. For a review see, e.g., [6] and references therein. Current issues in the experiment-theory dialogue are summarized, e.g., in [7]. Aspects of quarkonium production at LHC are discussed, e.g., in [8, 9] and new information for its $R_{AA}(\text{CNM})$ baseline are given in [10].

The suppression of charmonium (more general, heavy quarkonium suppression), due to color screening, was suggested to be a signal of QGP formation [11, 12]. The works [13, 14, 15] have studied the dissociation of quarkonium (charmonium and bottomonium)

by screening in a hot plasma. The binding energy of the heavy quark-antiquark pair in the quarkonium state vanishes at the respective Mott temperature where the bound state merges the continuum of scattering states [16, 17]. Below the Mott temperatures, the binding energies are already sufficiently lowered so that collisions with particles from the medium may have sufficient thermal energy to overcome the threshold for impact dissociation of quarkonium [18, 19, 20]. Both effects tend to wash out the pattern of sequential suppression for heavy quarkonia states expected from the “classical” picture of the Mott effect [21]. The description of quarkonia states in a hot QGP medium in the vicinity of the critical temperature should therefore treat bound and scattering states on an equal footing. This is appropriately achieved within a thermodynamical T-matrix approach, which has been developed to address the spectral properties of quarkonia [22] as well as open flavor meson states [23, 24, 25]. It is also worth noting that inelastic collisions are responsible for absorption of J/ψ in a hadron gas of light π and ρ mesons since the corresponding cross sections can be sufficiently large [20, 26, 27, 28, 29]. Once the partial densities of open charm mesons becomes nonnegligible, also the reverse processes of charmonium regeneration in channels like, e.g., $D + \bar{D} \rightarrow J/\psi + \rho$ will occur. J/ψ regeneration shall give important contributions to charmonium production

Email addresses: pena@ift.uni.wroc.pl (C. Peña),
blaschke@ift.uni.wroc.pl (D. Blaschke)

in heavy-ion collisions already at RHIC and the more at the LHC [30, 31, 32, 33, 34, 35, 36]

Another very interesting alternative is the channel $D + \bar{D}^* \rightarrow J/\psi + \rho$ [14] where as a “molecular” bound state of D and \bar{D}^* with binding energy below 1 MeV the exotic state X(3872) is discussed [7, 37, 38] which was recently discovered by BaBar [39] and subsequently confirmed by other experiments.

It has been shown that as long as medium effects can be embodied in a gaussian action, the $Q\bar{Q}$ propagator obeys a closed temporal evolution equation whose large-time behavior is governed by an effective potential. The latter, besides screening, displays also an imaginary part related to collisions [40, 41]. The determination of this imaginary part also provides insight into how the anisotropy of the medium relates with the width of the states [42, 43]. The use of complex potentials for describing data of charmonium suppression in pp and pA collisions has been documented in [44, 45, 46, 47]. An application of a time-dependent harmonic oscillator (THO) model with a complex oscillator frequency to experimental data of charmonium production in AA collisions has recently been given [14, 48]. This application predicted the formation of resonances nearby the onset of charmonium suppression (Mott transition) [49]. This model exhibits confinement in the sense that the potential grows quadratically with the separation distance of the $Q\bar{Q}$ pair.

In this work we consider such quantum-mechanical model for studying the role of static screening and absorption/regeneration kinetics for the quarkonium time evolution. The THO model for the production of $Q\bar{Q}$ pairs is a generalization of the Matsui formula [50] to a complex $Q\bar{Q}$ potential. The quantum mechanical evolution, as a function of the time t is encrypted in the evolution amplitude $U(\vec{r}, \vec{r}_0, t)$ for the initial $Q\bar{Q}$ state $\phi_{Q\bar{Q}}$. We have examined two alternatives for the initial state: it can be taken as a delta function [14, 48] or as a Gaussian [49]. The time dependence originates from the temperature evolution of the medium $T(\tau)$ which is assumed to obey total entropy conservation. In order to account for hot medium effects produced in AA collisions, the temperature dependence of the complex oscillator frequency $\omega^2(T)$ stands for screening, absorption and regeneration in a unified approach. By taking different ansätze for $\omega^2(T)$, we show that the THO model can describe the behavior of the measured J/ψ yield over the expected CNM effects $R_{AA}/R_{AA}(\text{CNM})$, as a function of the multiplicity of charged particles. Our method can be applied for more realistic cases, even for a $Q\bar{Q}$ Hamiltonian containing a complex confined potential in better agreement with Lattice QCD (LQCD) as the given in

[42, 43].

We pay special attention to the In-In data [4] taken at CERN SPS since they have the highest precision. Interestingly, they exhibit a peculiar shape (“wiggles”) [14, 49]. The wiggle turns out to be important since it appears around the estimated temperature for dissociation of charmonium ($\sim 1.3 T_c$ with $T_c = 0.154$ GeV [51]), which can be defined as the temperature for its Mott transition. Our novel result with the complex THO model suggests that such peculiar behavior can be mapped into $\Im[\omega^2(T)]$, in other words into the imaginary part of the $Q\bar{Q}$ potential. We examine whether the production of the X(3872) resonance can contribute to the in-medium $Q\bar{Q}$ hamiltonian.

2. Suppression factor for quarkonium

The survival probability (suppression factor) for J/ψ is defined in [50]

$$S_{\psi_n}(t) = \frac{\left| \int d^3r \psi_n^*(\vec{r}) \phi_{Q\bar{Q}}(\vec{r}, t) \right|^2}{\left| \int d^3r \psi_n^*(\vec{r}) \phi_{Q\bar{Q}}(\vec{r}, 0) \right|^2}, \quad (1)$$

This expression was published in bra-ket representation by Cugnon et al. [45]. This is a generalization of the Matsui approach to an arbitrary initial state [49]. The intermediate $Q\bar{Q}$ state is given by

$$\phi_{Q\bar{Q}}(\vec{r}, t) = \int d^3r_0 \phi_{Q\bar{Q}}(\vec{r}_0, 0) U(\vec{r}, \vec{r}_0, t), \quad (2)$$

where $\phi_{Q\bar{Q}}(\vec{r}_0, 0)$ represents the initial $Q\bar{Q}$ state at the position \vec{r}_0 and time $t = 0$. In the following we shall assume that the quantum number n , on the quarkonium state ψ_n , stands for the principal, angular and azimuthal quantum numbers. The suppression factor can be generalized to the case of nonsingular complex potentials and be applied to the QGP diagnostics in collisions of heavy ions with mass number A when identified with the experimentally determined quantity

$$\frac{R_{AA}}{R_{AA}(\text{CNM})} =: S_{\psi_n}(t) \quad (3)$$

where $R_{AA}(\text{CNM})$ accounts for the CNM effects from charmonium absorption in cold nuclear matter and modification of charm production by shadowing/antishadowing of gluon distribution functions in the CM of the colliding nuclei. Both effects are accessible by analysis of pA collision experiments, see [1, 6] and references therein. We restrict our discussion here to ground state charmonium at rest in the QGP medium ($p_T = y = 0$) so that the discussion of Lorentz boost effects on the formation process can be omitted. We

include, however, the feed-down from higher charmonia states which are discussed more in detail elsewhere [48, 49].

The next section is dedicated to the application of the generalized Matsui approach. To this end, we start calculating the evolution amplitude $U(\vec{r}, \vec{r}_0, t)$. As an example we consider the THO Hamiltonian to model the $Q\bar{Q}$ interaction.

3. Time-dependent harmonic oscillator model

For our discussion of the quantum mechanical evolution of quarkonia in an evolving QCD plasma state, we will employ here a generalization of the harmonic oscillator model [50] to a time-dependent one with nonsingular complex squared oscillator frequency (THO model). The merit of such a model is its simplicity and transparency as well as its tractability [14, 48, 49]. Aspects of an optical potential for the propagation of charmonia through a medium have been already discussed, e.g., for cold nuclear matter in [46, 52] and for a quark-gluon plasma in [45, 53]. We consider the time-dependent Hamiltonian for heavy quarkonia in the form

$$H(\tau) = \frac{p^2}{2\mu} + \frac{\mu}{2}\omega^2(\tau)r^2(\tau), \quad (4)$$

where $\mu = m_Q/2$ is the reduced mass and m_Q the heavy quark mass. The squared complex oscillator frequency $\omega^2(\tau)$ has an implicit time dependence due to the temperature evolution $T(\tau)$ of the system surrounding the evolving heavy quarkonium state. The quadratic dependence of the imaginary part of the (optical) oscillator potential is motivated by the phenomenon of color transparency, see also [54] and references therein.

The general classical trajectories for the Hamiltonian (4) can be found in [14, 48, 49, 55, 56, 57] and references therein. It is given by a linear combinations of the two solutions

$$r_{1,2}(\tau) = \rho(\tau) \exp(\pm i\phi(\tau)), \quad \phi(\tau) = \int \frac{d\tau}{\rho^2(\tau)}. \quad (5)$$

The amplitude $\rho(\tau)$ fulfills the Ermakov equation [49, 56, 57]

$$\ddot{\rho}(\tau) + \omega^2(\tau) \rho(\tau) - \frac{1}{\rho^3(\tau)} = 0, \quad (6)$$

for which exact solutions exist. The initial and final conditions of the oscillator are defined as $\vec{r}(0) = \vec{r}_0$ and $\dot{\vec{r}}(t) = \vec{r}$, respectively. This allows to evaluate the transition amplitude as a function of time using path integral

methods [48, 49, 58]

$$U(\vec{r}, \vec{r}_0, t) = \left[\frac{\mu \rho(t) \rho^{-1}(0) \dot{\phi}(t)}{2\pi i \sin(\phi(t) - \phi(0))} \right]^{3/2} e^{iS_{cl}}, \quad (7)$$

where the classical action is exactly calculated by $S_{cl} = \frac{\mu}{2} (\vec{r} \cdot \dot{\vec{r}} - \vec{r}_0 \cdot \dot{\vec{r}}_0)$ [49, 58]. Additionally the initial conditions for the Ermakov equation (6) are defined as $\rho(0) = \frac{1}{\sqrt{\omega(0)}}$, $\dot{\rho}(0) = 0$.

4. Applications to Heavy Ion Collisions

In the following we show that the anomalous J/ψ suppression in SPS, RHIC, and LHC experiments can be simultaneously described with the natural assumption that above the critical temperature the relevant screening of the quarkonium interaction can be parameterized with a temperature dependent, complex oscillator strength. The time evolution of the temperature itself will be given by longitudinally boost invariant (Bjorken scaling) hydrodynamic evolution of a fireball volume $V(\tau_e)$ under entropy conservation

$$s(T(\tau_e))V(\tau_e) = \text{const}; \quad V(\tau_e) = A_T z(\tau_e). \quad (8)$$

The temperature dependence of the entropy density $s(T)$ is taken from recent lattice QCD simulations [51] which are well parameterized by the simple ansatz [14, 49]

$$s(T) = 9.0 T^3 \left[1 + \tanh\left(\frac{T - 0.189}{0.534 T}\right) \right], \quad (9)$$

see Fig. 1.

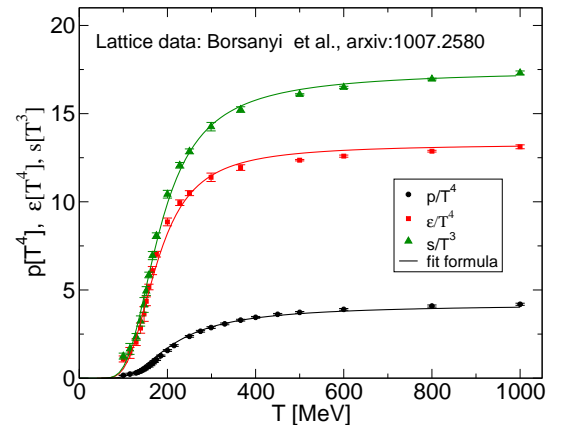


Figure 1: Recent results (data points) for the equation of state from lattice QCD [51] compared to the fit formula (9) employed here.

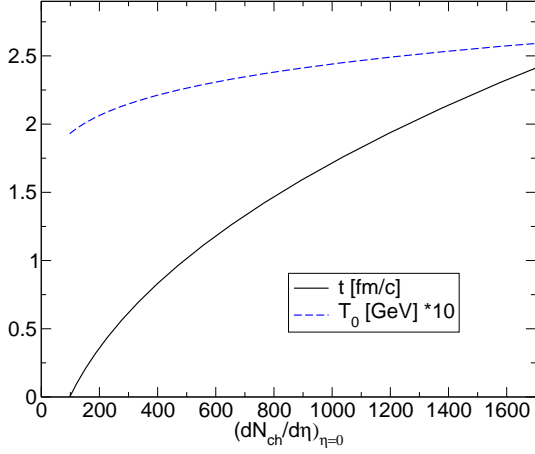


Figure 2: Initial temperature T_0 and time interval $t = \tau_f - \tau_0$ for the evolution of the $Q\bar{Q}$ state from formation at τ_0 to freeze-out at τ_f as a function of the measured charged particle yields per pseudorapidity interval $(dN_{ch}/d\eta)_{\eta=0}$.

The initial values of temperature correspond to initial entropy densities given by the Bjorken formula [59]

$$s_0 = \frac{3.6}{A_T \tau_0} \left(\frac{dN}{dy} \right)_{y=0}, \quad (10)$$

where the transverse overlap area A_T is taken in this work as [14, 49]

$$A_T = (4.8 \text{ fm}^2) \left[\left(\frac{dN_{ch}}{d\eta} \right)_{\eta=0} \right]^{0.57}. \quad (11)$$

We found the parametrization by fitting the average values of the overlap area for PbPb. The latter was obtained from Monte Carlo calculations performed in Ref. [5]. Additionally the transformation [5, 59] $\left(\frac{dN}{dy} \right)_{y=0} = 1.04 \times \frac{3}{2} \times \left(\frac{dN_{ch}}{d\eta} \right)_{\eta=0}$ has been used.

We are interested in the time evolution of the quarkonium state in the cooling fireball medium described by the thermal history $T(\tau)$ starting from $\tau = \tau_0 = 1.0$ fm/c until the freeze-out of the effective THO potential parameters at $T_f = T(\tau_f) = 0.193$ GeV [49]. Here, we defined $\tau_f = \tau_0 s(T_0)/s(T_f)$. In Fig. 2 we show the initial temperature $T_0 = T(\tau_0)$ and the duration of the quarkonium evolution until its freeze-out $t = \tau_f - \tau_0$ as a function of the charged particle multiplicity per pseudorapidity interval $(dN_{ch}/d\eta)_{\eta=0}$ characterizing the initial conditions of the fireball evolution¹.

¹In using Eq. (1) for describing anomalous J/ψ suppression due to a plasma medium switched on at a time τ_0 after the creation of the $Q\bar{Q}$ pair implies that the evolution of the latter before τ_0 is governed by a hermitian Hamiltonian which does not yet suffer a modification.

We consider the most suitable parametrization of the THO model with complex squared frequency given by² $\omega^2(T) = \Re[\omega^2(T)] + i \Im[\omega^2(T)]$. In this case screening, absorption and regeneration can be described simultaneously. Screening occurs when the real part of the squared frequency is $\Re[\omega^2(t)] < \omega_\psi^2$, where ω_ψ is the oscillator frequency for the J/ψ in vacuum. The case of absorption appears when the imaginary part is $\Im[\omega^2(t)] < 0$. The regeneration scenario [30, 31, 32, 33, 34, 35, 36] corresponds to $\Im[\omega^2(T)] > 0$ in the THO model which stems from the coupling of the charmonium hamiltonian to open charm channels. In addition we shall consider a gaussian wave function for initial $Q\bar{Q}$ state. Details are presented in [49].

The ground state of quarkonium can be identified with the 1S state of the harmonic oscillator [48, 50] given by $\psi_{000}(\vec{r}) = \psi_{000}(0) \exp\left(\frac{-r^2}{2 r_\psi^2}\right)$ with $r_\psi = \sqrt{\frac{1}{\mu \omega_\psi}}$. Calculations of the suppression factor with Dirac delta-shaped initial $Q\bar{Q}$ state were performed in [14] on the basis of Ref. [48]. In the following we use results for the J/ψ survival probability obtained in [49] using a gaussian shaped initial state and discuss the relation between parametrizations of the temperature dependent complex squared oscillator strength to experimental data on anomalous J/ψ suppression from SPS, RHIC and LHC. In particular, we discuss how accounting or not for the “wiggles” in the In-In data at SPS when parameterizing $\omega^2(T)$ will change predictions of the survival probability in the LHC domain.

5. Anomalous suppression from SPS to LHC

Anomalous suppression, the deviation from unity of experimental data for the J/ψ production ratio normalized to the expectation accounting for CNM effects (3), is considered as a key indicator for QGP formation in heavy-ion collisions. This effect, first observed at CERN SPS for Pb-Pb collisions at $\sqrt{s} = 17$ GeV, has been qualitatively confirmed by RHIC experiments with Au-Au interactions at $\sqrt{s} = 200$ GeV whereby three particularly interesting observations were made

- (i) the suppression is stronger at forward and backward rapidities rather than at midrapidity where the particle densities are highest,
- (ii) the onset of anomalous suppression and its dependence on centrality scales with the charged particle

²Note that in Ref. [14] a different convention for the THO frequency has been used.

density at midrapidity rather than with energy density.

- (iii) the rather precise data of the NA60 collaboration for In-In collisions show a dip in the centrality dependence of the anomalous J/ψ suppression ratio [4, 3].

While (i) is caused mainly by antishadowing and to some extent by geometry [60], the second finding is still not understood. For the puzzling In-In dip a suggestion has been made in [14] where this feature could be reproduced within the generalized Matsui approach by a subtle interplay of screening and absorption in the parametrization of the temperature dependence of the oscillator frequency. For the details see [49]. According to this picture, the dip reflects a nonmonotonous temperature behavior of the confining potential due to a resonance-like contribution in $\Re[\omega^2(T)]$. This calculation is rather susceptible to changes in the absorptive part in the complex oscillator strength, basically as a consequence of the Dirac delta distribution for the initial $Q\bar{Q}$ state.

In the present work we investigate the role of $\Im[\omega^2(T)]$ in reproducing the dip in In-In data, see Fig. 3 and Fig. 4. The parametrization used here allows a description of screening, absorption and regeneration simultaneously. Additionally, we employ for the initial $Q\bar{Q}$ state the gaussian shape given in [49]. For the LHC data on J/ψ suppression we employ recent results of the ALICE collaboration [61]. For estimating the CNM effects which are not measured yet at LHC, we deduce an error band guided by theoretical estimates in Ref. [62] and shown as the cyan hatched region in Figs. 3-5.

For an additional discussion of the behavior of the imaginary part of the $Q\bar{Q}$ potential shown in Fig. 4 we refer to a separate analysis of the $Q\bar{Q}$ plasma Hamiltonian [63] and the discussion of the role of the X(3872) particle and the spectral function of ρ meson in a quark meson plasma in this context [14, 49]. It is worth noting that the wiggle pattern in the In-In data is located in the region of temperatures $1.3 \leq T/T_c < 1.4$ [14, 49]. The influence of this wiggle on the charmonium suppression in the LHC region with charged particle densities exceeding the ones reached at RHIC is explored in Fig. 5. In this figure the two LHC predictions are completely different above $dN_{ch}/d\eta \sim 700$ although the complex oscillator strength is the same above 0.23 GeV. How can this wiggle affect the LHC predictions so strongly? One explanation can be seen in the survival probability (1) which encodes the quantum time evolution of the quarkonium state. As we have described above, the time evolution of the complex oscillator frequency is implied

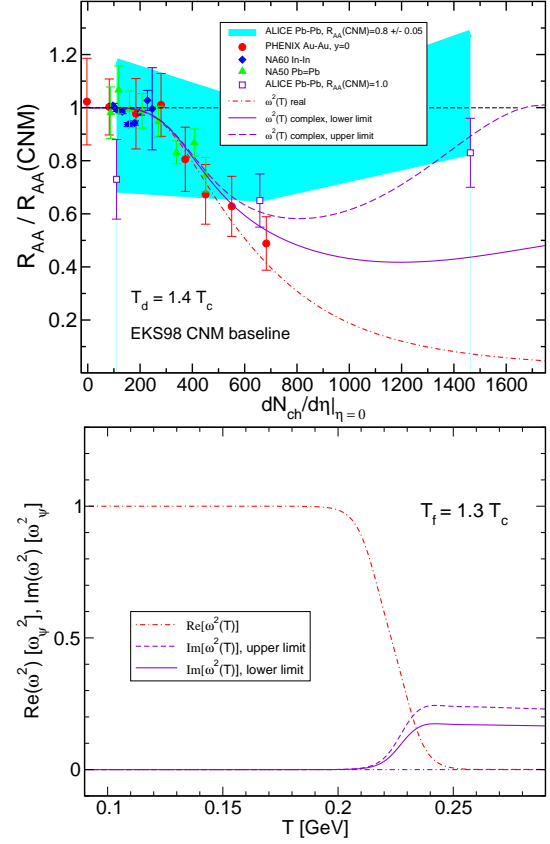


Figure 3: Predictions of the quantum mechanical THO model for charmonium suppression at CERN and RHIC. The LHC data are described by a purely imaginary part of the $Q\bar{Q}$ Hamiltonian.

by its assumed temperature dependence using the temperature evolution of the plasma $T(\tau)$ which follows from entropy conservation under Bjorken expansion (8) with the fit of the lattice QCD data for the entropy density (9).

The predictions for LHC are affected by the value of the oscillator strength at $T = T_f \sim 1.3 T_c$ where the complex frequency $\omega(T_0)$ enters the transition amplitude $U(\vec{r}, \vec{r}_0, t)$ (see Eq. (7)) through the condition $\rho(0) = 1/\sqrt{\omega(0)}$ and is determined by the equality $\omega(T_0) = \omega(T_f)$.

6. Conclusion

Recent studies of heavy quarkonia correlators and spectral functions at finite temperature in lattice QCD and systematic T-matrix approaches using QCD motivated finite-temperature potentials support that heavy quarkonia dissociation shall occur in the temperature range $1.2 \leq T_d/T_c \leq 1.5$ whereby the interplay of

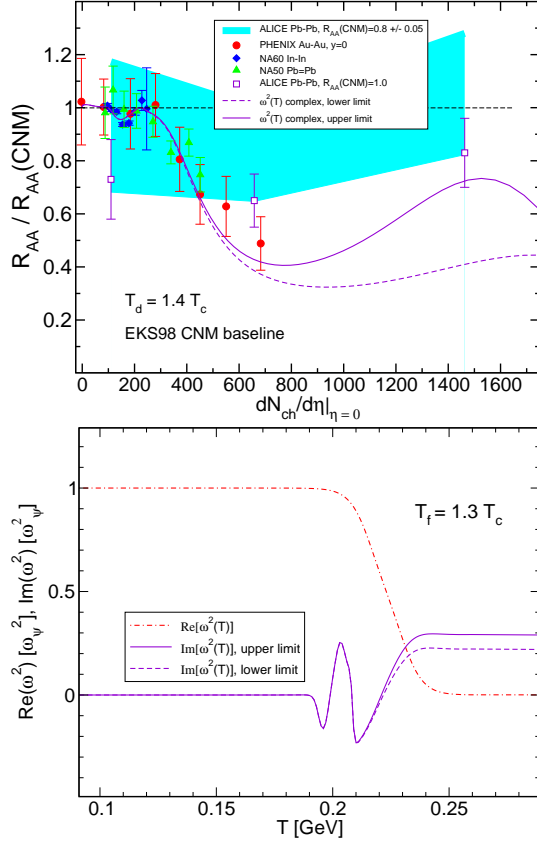


Figure 4: The same as Fig. 3, but fitting the “wiggles” in the In-In data by varying the imaginary part of the frequency. The dip is mostly described by absorption and regeneration on the region from 0.193 GeV to 0.21 GeV. The screening is rather visible above $T_f = 1.3 T_c$, as a consequence the production of charmonium decreases despite of the presence of the imaginary part. In order to exhibit a regeneration pattern in the domain of LHC beyond the RHIC data, the imaginary part of the squared oscillator frequency for temperatures above 0.23 GeV shall be larger than the corresponding one given in Fig. 3.

both screening and absorption processes is important. We have discussed these effects on the quantum mechanical evolution of quarkonia states within a time-dependent harmonic oscillator model with complex oscillator strength and compared the results for the survival probability with data for $R_{AA}/R_{AA}(\text{CNM})$ from SPS, RHIC and LHC experiments. Besides the traditional interpretation, with a threshold for the onset of anomalous suppression by screening and dissociation kinetics at $dN_{ch}/d\eta \sim 300$, we suggest an alternative arising from the attempt to model the dip of the suppression pattern of the rather precise NA60 data from In-In collisions at $dN_{ch}/d\eta \sim 150 - 250$. We suggest that this dip indicates the true threshold for the onset of anomalous suppression due to the coupling of charmonium to

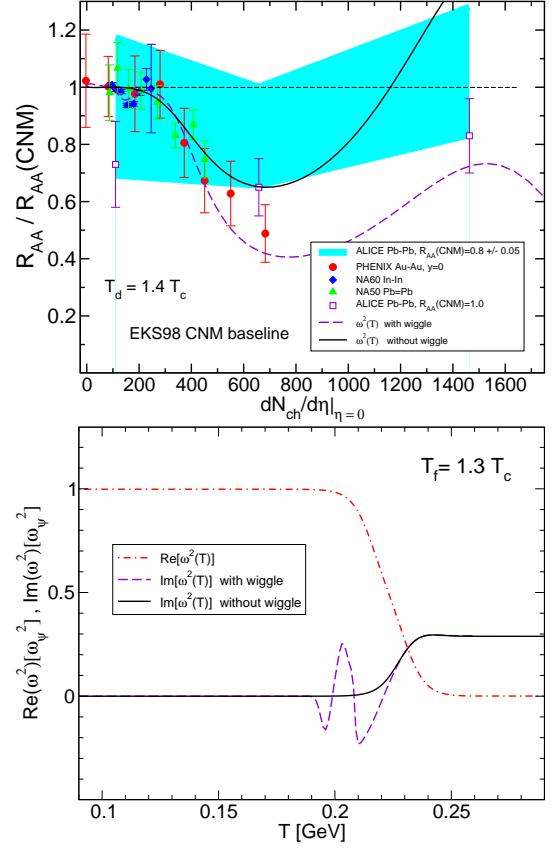


Figure 5: Influence of the wiggles on the charmonium suppression at the LHC region. This region corresponds to temperatures above 0.23 GeV see reference [49]. The two LHC predictions are completely different above $dN_{ch}/d\eta \sim 700$ although the complex oscillator strength above 0.23 GeV is the same. The difference is due to the different values of $\Im[\omega^2(\tau_f)]$.

the $\bar{D}^{*0}D^0$ channel with the recently discovered $X(3872)$ state. Although some details have been worked out in [38, 49], the theoretical basis for supporting this hypothesis has apparently been developed in plasma physics with the concept of a plasma Hamiltonian for nonrelativistic bound states like heavy quarkonia when they are immersed in a medium dominated by strong correlations like bound states. In the context of the theory of strongly correlated plasmas the formation and dissociation of bound states can be systematically addressed within cluster expansion techniques. With the advent of the new quality of the data from the ALICE experiment at LHC which provide yields of hidden ($Q\bar{Q} = J/\psi, \Upsilon, \dots$) and open heavy flavor ($Q\bar{q} = D, B, \dots$) mesons, it may be possible for the first time to measure the heavy quark association degree $n_{Q\bar{Q}}/n_{Q\bar{q}}n_{q\bar{Q}}$. Such quantity is of advantage for the QGP diagnostics not only because it is known for plasma diagnostics in stellar atmo-

spheres, semiconductor plasmas and nuclear matter, but in particular since it provides a new baseline for quantifying the J/ψ suppression effect. We will return to this issue in a separate work.

In the present work we have illustrated an alternative to the models of charmonium kinetics and statistical hadronization in the description of data for anomalous J/ψ suppression that utilizes the quantum mechanical formulation of quarkonia production with a complex Hamiltonian. To illustrate the method, a simple THO model with complex oscillator frequencies has been presented whereby the temperature dependence of the real and imaginary parts resulting from fitting heavy-ion collisions data of SPS, RHIC and LHC experiments on quarkonium production may allow to discuss the interplay of screening, absorption and regeneration of heavy quarkonia in these experiments. It is obvious that this tool may be further refined by using realistic temperature dependent complex potentials as motivated by lattice QCD studies. The quantum mechanical approach can also be exploited, e.g., to study the relative abundances of different excited states (Saha equation aspect of plasma diagnostics) and to study provide insights about the role of resonances at the open charm thresholds (most prominently the $X(3872)$) for the regeneration of J/ψ in an analogy to the role of the Hoyle state in element synthesis.

Acknowledgments

We would like to thank to R. Arnaldi, E. Scapparini and M. Leitch for providing us with data shown in Figs. 3 and 4. This work was supported by a grant of the Polish National Science Centre (NCN) within the “Maestro” programme.

References

- [1] E. G. Ferreira, F. Fleuret, J. P. Lansberg and A. Rakotozafindralandy, *Phys. Rev. C* **81**, 064911 (2010).
- [2] ALICE Collaboration, *Phys. Rev. Lett.* **109**, 072301 (2012).
- [3] R. Arnaldi [NA60 Collaboration], Presentation at the ECT* Workshop on “Quarkonium Production in Heavy-Ion Collisions”, Trento (Italy), May 25-29, 2009.
- [4] R. Arnaldi *et al.* [NA60 Collaboration], *Phys. Rev. Lett.* **99**, 132302 (2007).
- [5] S. S. Adler *et al.* [PHENIX Collaboration], *Phys. Rev. C* **71**, 034908 (2005) [Erratum-ibid. *C* **71**, 049901 (2005)].
- [6] R. Rapp, D. Blaschke and P. Crochet, *Prog. Part. Nucl. Phys.* **65**, 209 (2010).
- [7] N. Brambilla, S. Eidelman, B. K. Heltsley, R. Vogt, G. T. Bodwin, E. Eichten, A. D. Frawley and A. B. Meyer *et al.*, *Eur. Phys. J. C* **71**, 1534 (2011).
- [8] M. Bedjidian *et al.*, arXiv:hep-ph/0311048.
- [9] J. P. Lansberg *et al.*, *AIP Conf. Proc.* **1038**, 15 (2008).
- [10] R. Vogt, R. E. Nelson, A. D. Frawley, *AIP Conf. Proc.* **1038**, 15 (2008).
- [11] T. Matsui and H. Satz, *Phys. Lett. B* **178**, 416 (1986).
- [12] H. -T. Ding, A. Francis, O. Kaczmarek, H. Satz, F. Karsch and W. Söldner, *PoS LATTICE* **2010**, 180 (2010).
- [13] J. Jankowski, D. Blaschke and H. Grigorian, *Acta Phys. Polon. Suppl.* **3**, 747 (2010).
- [14] D. Blaschke, C. Peña, *Nucl. Phys. B. Proc. Suppl.* **214**, 137 (2011).
- [15] D. Blaschke, O. Kaczmarek, E. Laermann and V. Yudichev, *Eur. Phys. J. C* **43**, 81 (2005).
- [16] G. R. G. Burau, D. B. Blaschke and Y. L. Kalinovsky, *Phys. Lett. B* **506**, 297 (2001).
- [17] D. Blaschke, G. Burau, Yu. Kalinovsky and T. Barnes, *Eur. Phys. J. A* **18**, 547 (2003).
- [18] G. Röpke, D. Blaschke and H. Schulz, *Phys. Lett. B* **202**, 479 (1988).
- [19] G. Röpke, D. Blaschke and H. Schulz, *Phys. Rev. D* **38**, 3589 (1988).
- [20] D. Blaschke, Y. Kalinovsky and V. Yudichev, *Lect. Notes Phys.* **647**, 366 (2004).
- [21] S. Digal, P. Petreczky and H. Satz, *Phys. Rev. D* **64**, 094015 (2001).
- [22] D. Cabrera and R. Rapp, *Phys. Rev. D* **76**, 114506 (2007).
- [23] H. van Hees, M. Mannarelli, V. Greco and R. Rapp, *Phys. Rev. Lett.* **100**, 192301 (2008).
- [24] H. van Hees, M. Mannarelli, V. Greco and R. Rapp, *Eur. Phys. J. C* **61**, 799 (2009).
- [25] F. Riek and R. Rapp, *Phys. Rev. C* **82**, 035201 (2010).
- [26] C. Y. Wong, E. S. Swanson and T. Barnes, *Phys. Rev. C* **62**, 045201 (2000).
- [27] M. A. Ivanov, J. G. Körner and P. Santorelli, *Phys. Rev. D* **70**, 014005 (2004).
- [28] A. Bourque and C. Gale, *Phys. Rev. C* **80**, 015204 (2009).
- [29] D. B. Blaschke, H. Grigorian and Y. L. Kalinovsky, *Phys. Part. Nucl. Lett.* **9**, 7 (2012).
- [30] C. M. Ko, B. Zhang, X. N. Wang and X. F. Zhang, *Phys. Lett. B* **444**, 237 (1998) [nucl-th/9808032].
- [31] P. Braun-Munzinger and K. Redlich, *Eur. Phys. J. C* **16**, 519 (2000).
- [32] R. L. Thews, M. Schroedter and J. Rafelski, *Phys. Rev. C* **63**, 054905 (2001).
- [33] L. Grandchamp and R. Rapp, *Phys. Lett. B* **523**, 60 (2001).
- [34] L. Grandchamp and R. Rapp, *Nucl. Phys. A* **709**, 415 (2002).
- [35] A. Andronic, P. Braun-Munzinger, K. Redlich and J. Stachel, *J. Phys. G* **37**, 094014 (2010).
- [36] A. Andronic, P. Braun-Munzinger, K. Redlich and J. Stachel, *J. Phys. G* **38**, 124081 (2011).
- [37] T. J. Burns, F. Piccinini, A. D. Polosa and C. Sabelli, *Phys. Rev. D* **82**, 074003 (2010).
- [38] C. Peña, D. Blaschke, *Acta. Phys. Polon. B. Proc. Suppl.* **5**, 963 (2012).
- [39] B. Aubert, *et al.*, *Phys. Rev. D* **77**, 111101 (2008).
- [40] A. Beraudo, J. P. Blaizot and C. Ratti, *Nucl. Phys. A* **806**, 312 (2008).
- [41] M. Laine, O. Philipsen and M. Tassler, *JHEP* **0709**, 066 (2007).
- [42] A. Dumitru, Y. Guo, A. Mocsy, M. Strickland, *Phys. Rev. D* **79**, 054019 (2009).
- [43] M. Margotta *et al.*, *Phys. Rev. D* **83**, 105019 (2011).
- [44] E. Quack, *Nucl. Phys. B* **364**, 321 (1991).
- [45] J. Cugnon and P. B. Gossiaux, *Z. Phys. C* **58**, 95 (1993).
- [46] D. Koudela and C. Volpe, *Phys. Rev. C* **69**, 054904 (2004).
- [47] K. Martins, D. Blaschke and E. Quack, *Phys. Rev. C* **51**, 2723 (1995).
- [48] C. Peña, D. Blaschke, *Phys. Atom. Nucl.* **75**, 896 (2012).

- [49] C. Peña “Quantum Mechanical Model for Quarkonium Production in Heavy Ion Collisions,” PhD Thesis, University of Wrocław, January 2012.
- [50] T. Matsui, Ann. Phys. **196**, 182 (1989).
- [51] S. Borsanyi, G. Endrodi, Z. Fodor, A. Jakovac, S. D. Katz, S. Krieg, C. Ratti and K. K. Szabo, JHEP **1011**, 077 (2010).
- [52] B. Z. Kopeliovich and J. Raufeisen, Lect. Notes Phys. **647**, 305 (2004).
- [53] J. Cugnon and P. B. Gossiaux, Z. Phys. C **58**, 77 (1993).
- [54] D. Blaschke and J. Hüfner, Phys. Lett. B **281**, 364 (1992).
- [55] I. Gjaja and A. Bhattacharjee, Phys. Rev. Lett. **68**, 2413 (1992).
- [56] V. P. Ermakov, Appl. Anal. Discrete Math. **2**, 123 (2008).
- [57] A. D. Polyanin and V. F. Zaitsev, *Handbook of exact solutions for ordinary differential equations*, Chapman & Hall/CRC, Boca Raton (2003), p. 461;
P. G. L. Leach and K. Andriopoulos, Appl. Ann. Discrete Math. **2**, 146 (2008).
- [58] H. Kleinert, *Path integrals in Quantum Mechanics, Statistics, Polymer Physics, and Financial Markets*, World Scientific, Singapore (2006), pp. 114-115.
- [59] K. Yagi, T. Hatsuda and Y. Miyake, *Quark-Gluon Plasma*, Cambridge University Press (2005).
- [60] D. Prorok, L. Turko and D. Blaschke, Phys. Lett. B **690**, 352 (2010).
- [61] E. Scomparin [ALICE Collaboration], arXiv:1211.1623 [nucl-ex].
- [62] R. Vogt, Phys. Rev. C **81**, 044903 (2010).
- [63] D. Blaschke, DESY-PROC-2009-07; [arXiv:0912.4479 [hep-ph]].